NACA TN 3855

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3855

THE EFFECT OF FORWARD-FLIGHT SPEED ON THE PROPULSIVE CHARACTERISTICS OF A PULSE-JET ENGINE MOUNTED ON A HELICOPTER ROTOR

By Robert D. Powell, Jr.

Langley Aeronautical Laboratory
Langley Field, Va.

Washington
January 1957

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3855

THE EFFECT OF FORWARD-FLIGHT SPEED ON THE PROPULSIVE CHARACTERISTICS OF A PULSE-JET ENGINE MOUNTED ON A HELICOPTER ROTOR

By Robert D. Powell, Jr.

SUMMARY

The effect of rotor forward speed on the propulsive characteristics of a blade-tip-mounted helicopter-type pulse-jet engine has been determined in the Langley full-scale tunnel for various engine rotational speeds.

The effect of forward speed was to decrease mean engine thrust and increase engine specific fuel consumption. For a representative cruising forward-flight condition of 90 feet per second and an engine velocity of about 370 feet per second, a reduction in propulsive thrust of about 5.5 percent and an increase in minimum specific fuel consumption of about 4 percent from that obtained at zero forward speed are shown. For the most severe condition tested, a tip speed of 425 feet per second and a forward speed of 101 feet per second, a 50-percent reduction in thrust and a 100-percent increase in engine specific fuel consumption were obtained. Whirling at a rotor forward speed of zero resulted in about a 10- to 20-percent reduction in engine thrust from that obtained in tests of a nonwhirling engine as the centrifugal acceleration was increased from 178g to 286g.

INTRODUCTION

From a performance standpoint, the pulse-jet-powered helicopter rotor has reasonably high ratios of lift to fuel consumption as compared with other rotor jet-propulsion systems and therefore has been given consideration for the larger helicopter "load-lifter" configurations.

One of the problems encountered with blade-tip-mounted helicopter power plants that take in their air at the tip is the effect of varying inlet flow angle and varying dynamic pressure on engine performance in forward flight. In addition, there is the general problem of the detrimental effect of centrifugal forces on the engine propulsive characteristics as well as the problem of heating and dilution of the inlet air by the exhaust gases.

The hovering performance of a pulse-jet-powered rotor, as determined at the Langley helicopter tower, has been reported in reference 1, and the effects of centrifugal acceleration on the engine performance, as determined by comparison with the performance of the nonwhirling pulse-jet engine, have been discussed in reference 2. Reference 2 also contains data on the propulsive characteristics of a nonwhirling pulse-jet engine (having only minor differences from the one tested on the tower) at various Mach numbers and yaw angles. These data, although they provide basic information on the propulsive characteristics of the engine, cannot necessarily be expected to predict accurately the effect of forward flight on the performance of an engine when mounted at the tip of a helicopter rotor since the tests of reference 2 were made under steady-state conditions and were subject only to gravitational acceleration.

The investigation herein is a continuation of a general helicopter power-plant evaluation and considers the effect of forward flight on the propulsive characteristics of the whirling pulse-jet engine.

These tests were conducted at engine rotational tip speeds up to 425 feet per second and rotor forward speeds up to 101 feet per second. Several nozzle arrangements were tried to see whether fuel distribution and, consequently, engine thrust could be improved. The fuel flow ranged from that used at low engine thrust to the maximum flow rate at which stable engine operation could be maintained.

SYMBOLS

A_j	frontal area of pulse-jet engine, 69.5 sq in.
V_j	velocity of pulse-jet engine, ft/sec
$V_{j,corr}$	corrected velocity of pulse-jet engine, $V_j/\sqrt{\theta}$, ft/sec
F_p	mean propulsive thrust of pulse-jet engine (available thrust over and above engine drag), lb
F_p/δ	corrected mean propulsive thrust, lb
w_f	fuel mass-flow rate, lb/hr
$w_{f,corr}$	corrected fuel mass-flow rate, $\frac{w_f}{\delta\sqrt{\theta}}$, lb/hr

M forward-flight Mach number, ratio of tunnel air velocity to local velocity of sound

g acceleration due to gravity, ft/sec^2

Ω rotor angular velocity, radians/sec

μ ratio of rotor forward speed to engine rotational speed

θ ratio of absolute static temperature to standard NACA sea-level absolute temperature

δ ratio of absolute ambient pressure to standard NACA sea-level absolute pressure

APPARATUS AND TEST METHODS

This investigation was made in the Langley full-scale tunnel which has an open throat 30 feet high by 60 feet wide. A description of the tunnel can be found in reference 3.

Test Installation

Figures 1(a) and 1(b) show the test apparatus mounted in the tunnel. The center of the rotor was on the center line of the tunnel. The rotor was a two-blade teetering type with a radius of 19.40 feet to the center line of the jet engines. The blades were plywood covered and had a tubular steel main spar, NACA 23015 airfoil sections, and a torsional stiffness of about 4,000 inch-pounds per degree of twist. The rotor had the tip engines mounted so that the engine axis was horizontal when the rotor lift was zero. The outer 7 inches of the rotor blades consisted of an aluminum fairing which extended to the jet-engine shell (fig. 2). The fairing had projecting air intakes (1/2 inch by 1 inch) on the top and bottom surfaces and a leading-edge air intake (1.5 square inches) next to the engine shell to provide for engine cooling. The drag of these air intakes is considered to be part of the engine drag.

The rotor hub was mounted on a vertical shaft directly connected to the shaft of a vertically mounted electric motor. This motor was used to drive the rotor blades with and without engines attached to obtain the power requirements of the rotor blades. It was also used to maintain constant rotor speed by absorbing part of the pulse-jet engine power when the engines were operating. Measurements of torque, either supplied or absorbed, were made by electrical strain gages mounted on a necked-down portion of the vertical shaft between the rotor hub and the motor.

Fuel (80-octane white gasoline) was supplied to the engines at the tip of the blades by means of 1/4-inch steel tubing passing through the shaft and out through the blade spar. The fuel entered the shaft through a rotary seal at the base of the motor shaft. Fuel flow was measured by a rotating vane flowmeter. Initial ignition of the fuel in each engine was accomplished by two high-tension coils mounted on the rotor hub with a lead from each coil running through the blade spar to a small spark plug mounted in the side of the engine combustion chamber.

Engine

The pulse-jet engine used for this investigation was similar to those used in previous helicopter-tower and wind-tunnel tests (refs. 1 and 2). It had an operating frequency of about 100 cycles per second, weighed 36 pounds, and was 49.7 inches long. The maximum diameter was 9.4 inches. A sketch of the pulse-jet engine and the fairing between the engine and blade tip is shown in figure 2.

A conventional flapper-type valve box (see fig. 3(a)) was used on the engine. Figure 3(b) shows the arrangement of the moving parts of the valve box which consisted of a sandwich of one (0.005-inch-thick) phosphor-bronze strip (for even heat distribution) between two (0.006-inch-thick) blued-steel strips. These strips were 1 inch wide by 6 inches long. The spring constant of the valves was approximately 20 pounds per inch deflection of the valve tips.

All the fuel nozzles used in these tests were standard commercial oil-burner types and had a 60° spray cone angle. Previous comparisons of whirling and nonwhirling pulse-jet-engine performance (ref. 2) had indicated a decrease in engine thrust, presumably because of a centrifugal distortion of the fuel spray pattern. Accordingly, several nozzle arrangements which sprayed more fuel on the inboard side of the engine were tried and are shown in figure 4.

The data presented herein were obtained with nozzle configuration 4(a), which is different from the nozzle arrangement used in references 1 and 2 in that two extra fuel nozzles were added to the inboard side of the engine. This nozzle configuration consisted of four nozzles (one on each side) located immediately to the rear of the valve box with their spray axis normal to the engine flow (same as those of refs. 1 and 2) and two extra nozzles located on the inboard side of the engine immediately to the rear of the valve box $2\frac{1}{2}$ inches above and below the engine horizontal center line with their spray axis alined with the engine flow. All were number 7 nozzles. The nozzle number (fig. 4) refers to the fuel discharge rate in gallons per hour at a fuel pressure of 100 pounds per square inch.

Nozzle configuration 4(b), which is very similar to the nozzle arrangements used in references 1 and 2 in that most of the fuel is sprayed in immediately to the rear of the valve box and normal to the air flow, was also tested. No differences in engine propulsive characteristics between nozzle configurations 4(a) and 4(b) were apparent.

Another nozzle arrangement tried is shown in figure 4(c) and consisted of six nozzles directed inboard at a 45° angle and arranged along a central column. Engine propulsive characteristics were unaffected by this nozzle change except for a slight increase in maximum fuel flow.

Since previous hovering tests of jet-powered rotors indicated a temperature rise of the engine inlet air due to the exhaust of the preceding engine, an iron-constantan thermocouple was mounted about 4 inches ahead of the engine air inlet to measure the engine inlet-air temperature.

Test Procedure and Analysis

Inasmuch as the purpose of the investigation was to determine only the propulsive characteristics of the engines, all tests were made at zero rotor thrust. This condition greatly simplified the test procedure and the analysis of results. In effect, the rotor blades acted only as streamlined whirling arms to which the pulse-jet engines were attached. It was believed that the engine thrust would be practically identical with that obtained if the rotor were producing lift since it had been shown (ref. 2) that this type of engine was not affected by operation at airflow angles up to 20°.

All whirling tests were made under steady-state operating conditions. The test procedure consisted of maintaining the rotor tip speed constant by adjusting the input to the drive motor while varying the fuel-flow rate over the desired range at each of the four tunnel speeds (designated as rotor forward speeds).

The power requirements of the rotor blades at various rotor forward speeds without engines attached were determined directly from the motor shaft torque measurements. The propulsive thrust of the pulse-jet engine is defined as the thrust available over and above its own drag. It was calculated by assuming that the propulsive thrust of the two engines was equal to the sum of the thrust required to drive the blades without the engines attached and the tip thrust equivalent of the rotor torque absorbed by the electric motor. The total tip thrust equivalent of the rotor torque is calculated by dividing the torque absorbed by the electric motor by the distance from the center line of rotation to the center line of the jet engines. A fuel-pumping term corresponding to the force necessary to accelerate the fuel mass flow from zero velocity at the hub to engine speed was added to the whirling propulsive thrust to make the results directly comparable with the nonwhirling thrust obtained in reference 2.

The increase in temperature of the air through which the engine passed, caused by the exhaust of the previous engine, was measured and the corrections

$$w_{f,corr} = \frac{w_f}{\delta \sqrt{\theta}}$$

$$V_{j,corr} = \frac{V_j}{\sqrt{\theta}}$$

to the engine fuel flow and tip speed for this temperature rise have been applied. These corrections are outlined in reference 4. At high fuel flows and zero forward speed the maximum temperature rise was about 40°. As the forward speed was increased, the temperature rise decreased to about 10° to 15°.

The various quantities that were measured were as follows: barometric pressure and temperature of the tunnel air, inlet-air temperature of pulse-jet engine, fuel flow, electric motor torque, and shaft rotational speed. The estimated accuracies of the basic quantities measured in the tunnel tests are: rotor torque, ±10 foot-pounds; fuel flow rate, ±5 pounds per hour; rotational speed, ±1 revolution per minute. The overall accuracy of the plotted data is believed to be ±3 percent.

RESULTS AND DISCUSSION

The data presented herein were obtained with the fuel nozzle configuration shown in figure 4(a). The other nozzle configurations tried (figs. 4(b) and 4(c)) had little or no effect on engine thrust characteristics, although the configuration shown in figure 4(c) indicated improved valve life, possibly because of the cooling and shielding action of the fuel spray.

Power-Off Engine Drag

The engine drag was obtained by rotor torque measurements with and without the engines attached to the blades. In order to evaluate the interference of the engine-blade combination, drag values for the whirling engine blade of the present test were compared with drag values for the nonwhirling engine of reference 2. In the present tests the drag of the engine attached to the blade was measured and included the interference drag due to the presence of the engine on the blade, whereas the drag values measured in reference 2 were of the engine alone. The fairing of the blade to the engine was similar to that of the configuration of reference 2. The total drag (engine plus interference) is the difference between the rotor torques (with and without engines) divided by the product of the number of blades and the distance from the center of rotation to the engine center line. The total drag obtained for the engine plus interference was approximately 15 percent greater than that measured for the engine alone (ref. 2).

Operation at high tip speeds during engine burning tests necessitated reinforcing of the engine; this reinforcement in turn required a larger fairing (fig. 2). The increase in fairing size resulted in an additional 11-percent increase in total engine drag. This additional drag due to the large fairing was added to the engine propulsive thrust (as determined from the torque measurements in the present tests) and made the engine thrust values directly comparable with the thrust values of the nonwhirling engine obtained in reference 2. Inclusion of the drag due to this additional fairing with the thrust was considered reasonable since with appropriate materials and construction the additional fairing would not be necessary.

Power-On Engine Thrust Characteristics

The effect of rotor forward speed and whirling on the propulsive characteristics of the pulse-jet engine is shown in figure 5 in plots of mean engine thrust against fuel flow rate for various forward speeds at each of four rotor tip speeds. The mean engine thrust is the time-averaged engine thrust throughout one revolution of the rotor shaft. A curve of the engine nonwhirling thrust characteristics (taken from ref. 2) is also shown in each figure for comparison with the whirling data.

Effect of whirling.- The data for the whirling engine obtained in the Langley full-scale tunnel at a forward speed of zero (fig. 5) show a somewhat lower fuel consumption for a given thrust (approximately 10 pounds per hour less over most of the usable operating range) than that obtained from the helicopter-tower tests of reference 1. No explanation for this difference is available at this time; however, it is believed that the wind-tunnel data are the more accurate owing to the improved fuel-flow instrumentation.

The comparison of the data obtained at a forward speed of zero for the nonwhirling and the whirling engines (fig. 5) shows the detrimental effect of whirling (or, presumably, of centrifugal forces) on the engine thrust. The decrease due to whirling alone is 10 to 15 percent of the thrust over most of the operating range; for the case of the highest tip speed (and thus, highest centrifugal forces) tested (fig. 5(d)), there was about a 20-percent reduction in engine thrust.

Effect of forward speed.- Figure 5(a) shows that rotor forward speed has only a slight effect on the engine propulsive characteristics at low rotor tip speeds. At the higher tip speeds (figs. 5(b), 5(c), and 5(d)), the engine thrust shows a significant reduction of 3 to 50 percent with increasing forward speed.

Part of the reduction in mean engine thrust shown for the forward-flight conditions in figure 5 is due to the large changes in the resultant engine velocity encountered during rotor forward flight. On the advancing side of the rotor where the forward speed and engine rotational speed are additive, the engine propulsive thrust decreases because of the increased engine speed. Conversely, on the retreating side of the rotor disk, the engine thrust is increased because of the decreased speed. Since the characteristic of the pulse jet is such that the rate of decrease of engine thrust increases with speed, the net result is a decrease in mean engine thrust in forward flight.

At the highest tip speed (fig. 5(d)) and highest rotor forward speed, considerable difficulty was encountered in keeping the engine running and thus only the maximum-thrust points were determined. Even for this maximum-thrust case, the engine resonating action was erratic and a trail of flame could be seen on the retreating side of the rotor disk. The high fuel-air ratio on the retreating side could not of itself explain this phenomenon, since data on a similar nonwhirling engine operating at speeds corresponding to the retreating engine speed (324 feet per second) show that this engine should have stable operation at much higher fuel flows than that reached in this particular test condition. One possible explanation of the failure of the engine to operate at this fuel flow on the retreating side is distortion of the fuel spray pattern caused by a combination of the high centrifugal accelerations and reduced combustion-chamber velocities associated with the lower resultant engine velocities on the retreating side of the rotor disk.

Figure 6 shows the reduction in mean engine thrust from the value for the nonwhirling engine (ref. 2) as a function of engine centrifugal acceleration and rotor-tip-speed ratio for two representative fuel flows (240 and 280 pounds per hour).

Figure 6(a) $(w_{f,corr} = 240 \text{ lb/hr})$ shows that losses in engine thrust increase rapidly with increase in centrifugal acceleration even at a rotor forward speed of zero. Superimposing a forward speed causes more thrust reduction, particularly at the higher tip speeds. It is apparent that one major factor affecting the engine thrust characteristics in forward flight is the sensitivity of the engine operation to the combination of high centrifugal accelerations and high forward speeds.

Figure 6(b) ($w_{f,corr}$ = 280 lb/hr) is essentially similar to figure 6(a) except at the higher centrifugal accelerations, where the percent reduction in thrust is not as high as that obtained at the lower fuel rate shown in figure 6(a). The reduction in thrust at the lowest centrifugal acceleration (in the vicinity of 180g) results from operation of the engine at a fuel flow rate very close to the maximum for stable combustion at this lower engine velocity.

Comparison with calculations.- On the basis of the data from reference 2, which covered a range of engine speeds and yaw angles, calculations were made of the mean thrust per revolution that would be expected for the present test conditions. These calculations thus took into account the variation of engine speed and yaw angle around the rotor disk but not the centrifugal and unsteady effects associated with rotational and forward flight.

At the lowest engine whirling tip speed of 335 feet per second, the experimental decrease in mean engine thrust as a function of rotor forward speed (except for the initial decrease due to whirling) was about the same as that calculated. At the highest tip speed and centrifugal accelerations, however, the calculation indicated only about a 2- to 3-percent decrease in mean engine thrust whereas actual experimental data showed about a 50-percent reduction. Obviously then, data from a nonwhirling engine cannot be used to predict accurately the effects of rotor forward speed on the mean engine thrust for this particular engine.

Engine Performance Summary

A convenient method of illustrating engine performance is provided by plotting mean propulsive thrust per unit frontal area at minimum specific fuel consumption and minimum specific fuel consumption in pounds of fuel per hour per horsepower as a function of rotor forward speed. Such a plot is shown in figure 7. Data are presented for various engine rotational velocities and, thus, various centrifugal loadings.

At engine rotational velocities of 335, 369, and 402 feet per second (corresponding to centrifugal accelerations of 178g, 216g, and 264g), the mean propulsive thrust at minimum specific fuel consumption shows a slight decrease as rotor forward speed increases (fig. 7). For example, at a rotational velocity of 369 feet per second, the mean propulsive thrust at minimum specific fuel consumption decreases from a value of 0.90 to 0.80 as rotor forward speed increases from 0 to 100 feet per second. At the higher rotational speed of 425 feet per second (centrifugal acceleration of 286g), the mean propulsive thrust is about 0.76 pound per square inch of frontal area at a rotor forward speed of zero and decreases to about 0.4 pound per square inch of frontal area at a rotor forward speed of 100 feet per second.

The engine minimum specific fuel consumption at the lower tip speeds of 335, 369, and 402 feet per second shows only a slight increase for forward speeds up to 100 feet per second. At a rotational engine speed of 425 feet per second, however, there is a gradual increase in specific fuel consumption as rotor forward speed is increased up to 67 feet per second; this increase is followed by a rapid increase in specific fuel consumption as the forward speed is further increased to the maximum of 101 feet per second.

The maximum thrust per unit frontal area and minimum specific fuel consumption for this engine when it is whirling occur at engine velocities of about 370 feet per second (216g) throughout the entire range of rotor forward speeds tested. At this engine velocity and at a representative cruising flight speed of about 90 feet per second, the maximum mean engine propulsive thrust per square inch of frontal area is about 0.85 pound. The corresponding minimum specific fuel consumption is about 7.0 pounds of fuel per hour per horsepower. This flight condition results in about a 5.5-percent reduction in mean propulsive thrust at minimum specific fuel consumption and about a 4-percent increase in specific fuel consumption as compared with that obtained at a rotor forward speed of zero; whereas the more severe condition of a tip speed of 425 feet per second and a forward speed of 101 feet per second results in a 50-percent reduction in thrust and a 100-percent increase in engine specific fuel consumption.

CONCLUSIONS

An investigation to determine the effect of forward flight on the propulsive characteristics of a helicopter-rotor blade-tip-mounted pulse-jet engine has been made in the Langley full-scale tunnel. Some of the more pertinent findings of these tests are as follows:

1. The effect of forward flight, in general, is a reduction in the mean engine propulsive thrust and an increase in engine specific fuel consumption. For a particular flight condition in which the engine speed is about 370 feet per second and the rotor forward speed is 90 feet per second, a decrease of about 5.5 percent in mean engine thrust and an increase of about 4 percent in engine specific fuel consumption as compared with that obtained at zero forward speed are shown. For the most severe flight condition of the investigation, a tip speed of 425 feet per second and a forward speed of 101 feet per second, the engine thrust is decreased 50 percent and the engine specific fuel consumption is increased 100 percent.

2. The effect of whirling at a rotor forward speed of zero on the engine thrust is a 10- to 20-percent reduction from that obtained in the tests of the nonwhirling engine as the centrifugal acceleration is increased from 178g to 286g.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., August 7, 1956.

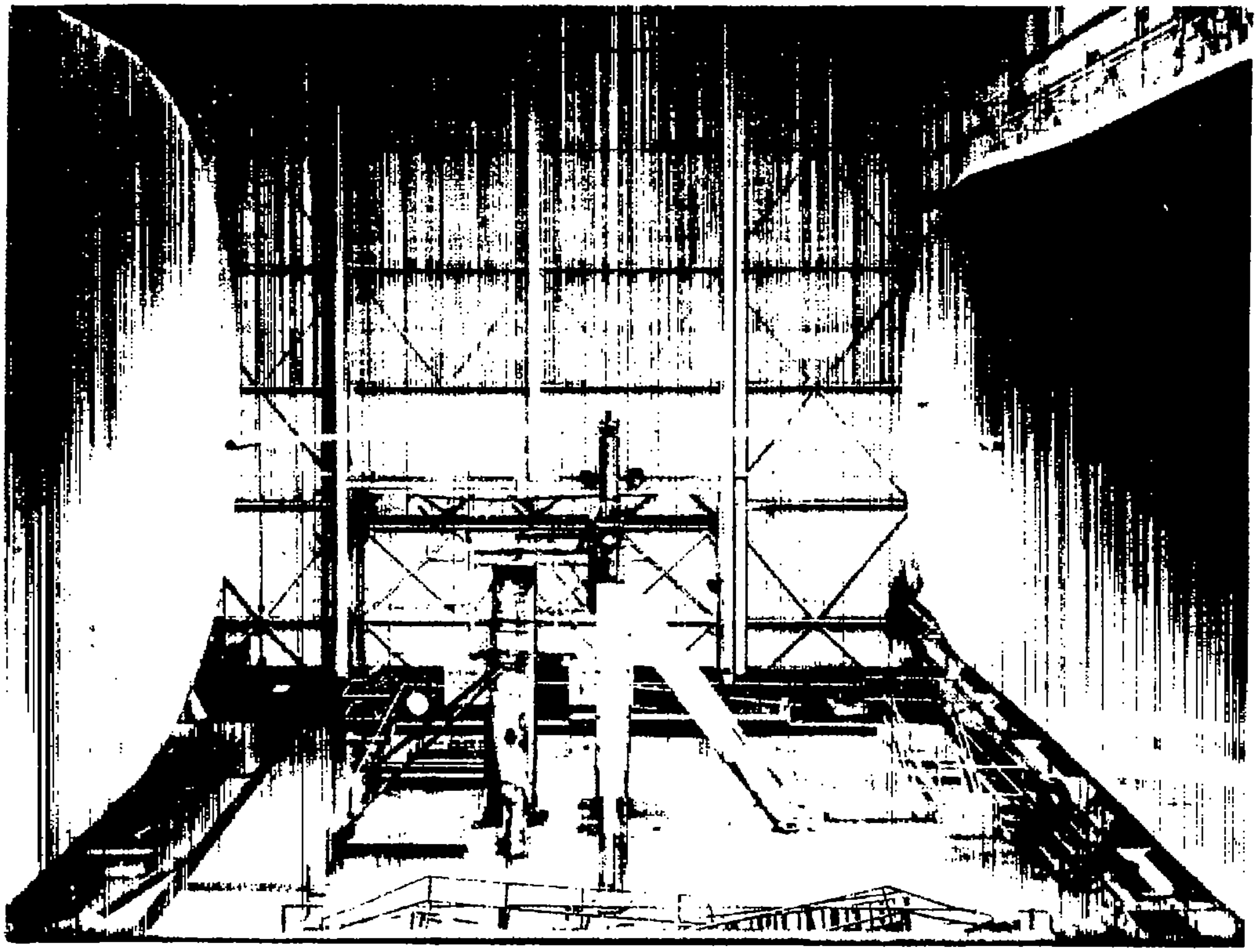
REFERENCES

1. Radin, Edward J., and Carpenter, Paul J.: Investigation of a Pulse-Jet-Powered Helicopter Rotor on the Langley Helicopter Test Tower. NACA RM L53L15, 1954.

2. Carpenter, Paul J., Shivers, James P., and Lee, Edwin E., Jr.: Investigation of the Propulsive Characteristics of a Helicopter-Type Pulse-Jet Engine Over a Range of Mach Numbers and Angle of Yaw. NACA TN 3625, 1956.

3. DeFrance, Smith J.: The N.A.C.A. Full-Scale Wind Tunnel. NACA Rep. 459, 1933.

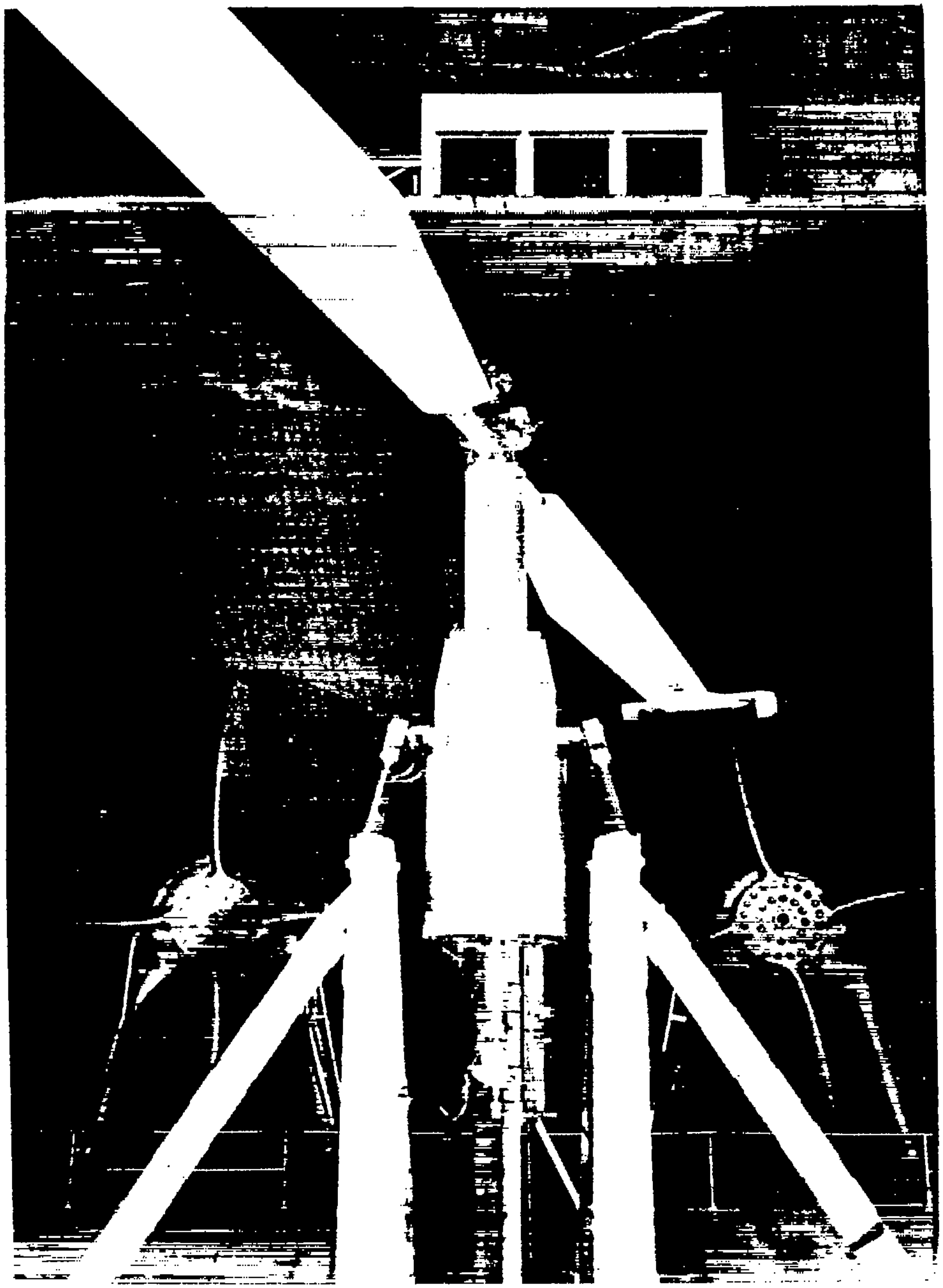
4. Sanders, Newell D.: Performance Parameters for Jet-Propulsion Engines. NACA TN 1106, 1946.



L-89256

(a) Overall view.

Figure 1.- Helicopter rotor powered by pulse-jet engine and mounted in the Langley full-scale tunnel.



L-89090

(b) Closeup view.

Figure 1.- Concluded.

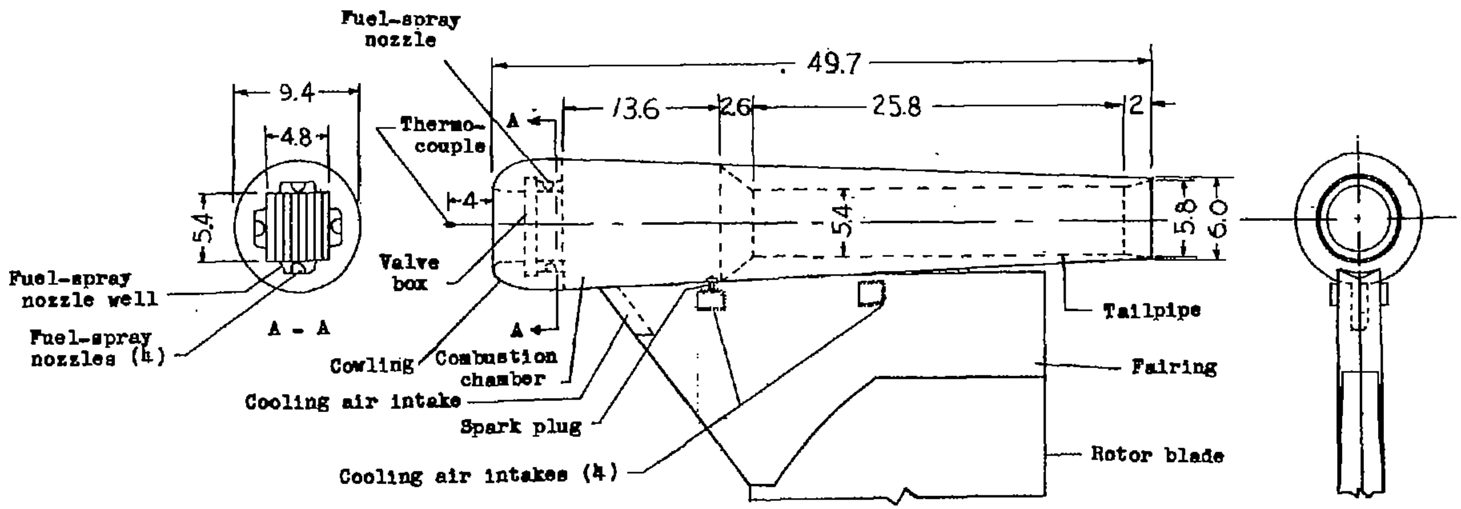
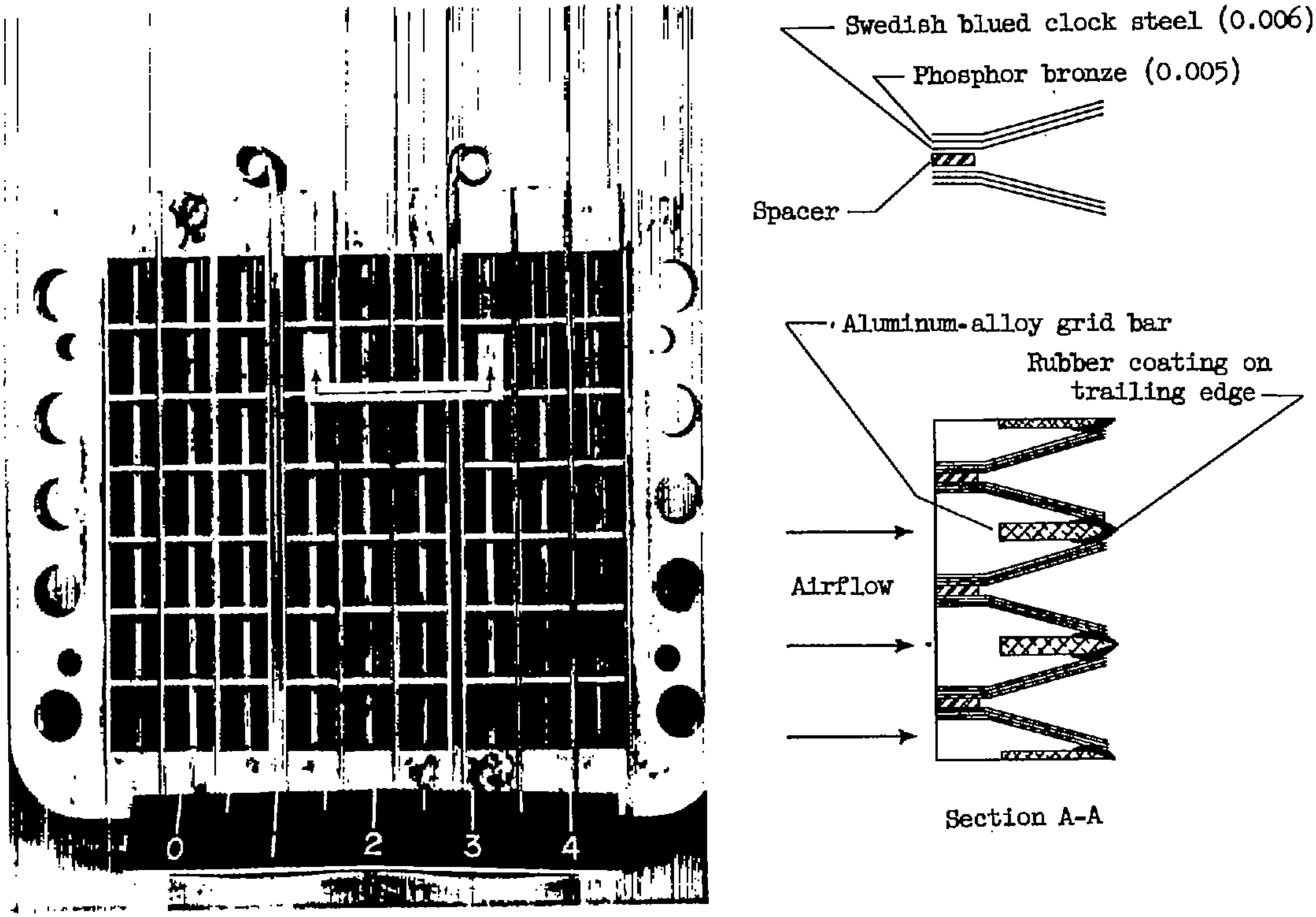


Figure 2.- Sketch of the pulse-jet engine. All dimensions are in inches. Numbers inside engine indicate inside-diameter dimensions.



L-80325.2

(a) Front view. (b) Valve detail.

Figure 3.- Pulse-jet-engine flapper-type valve box.

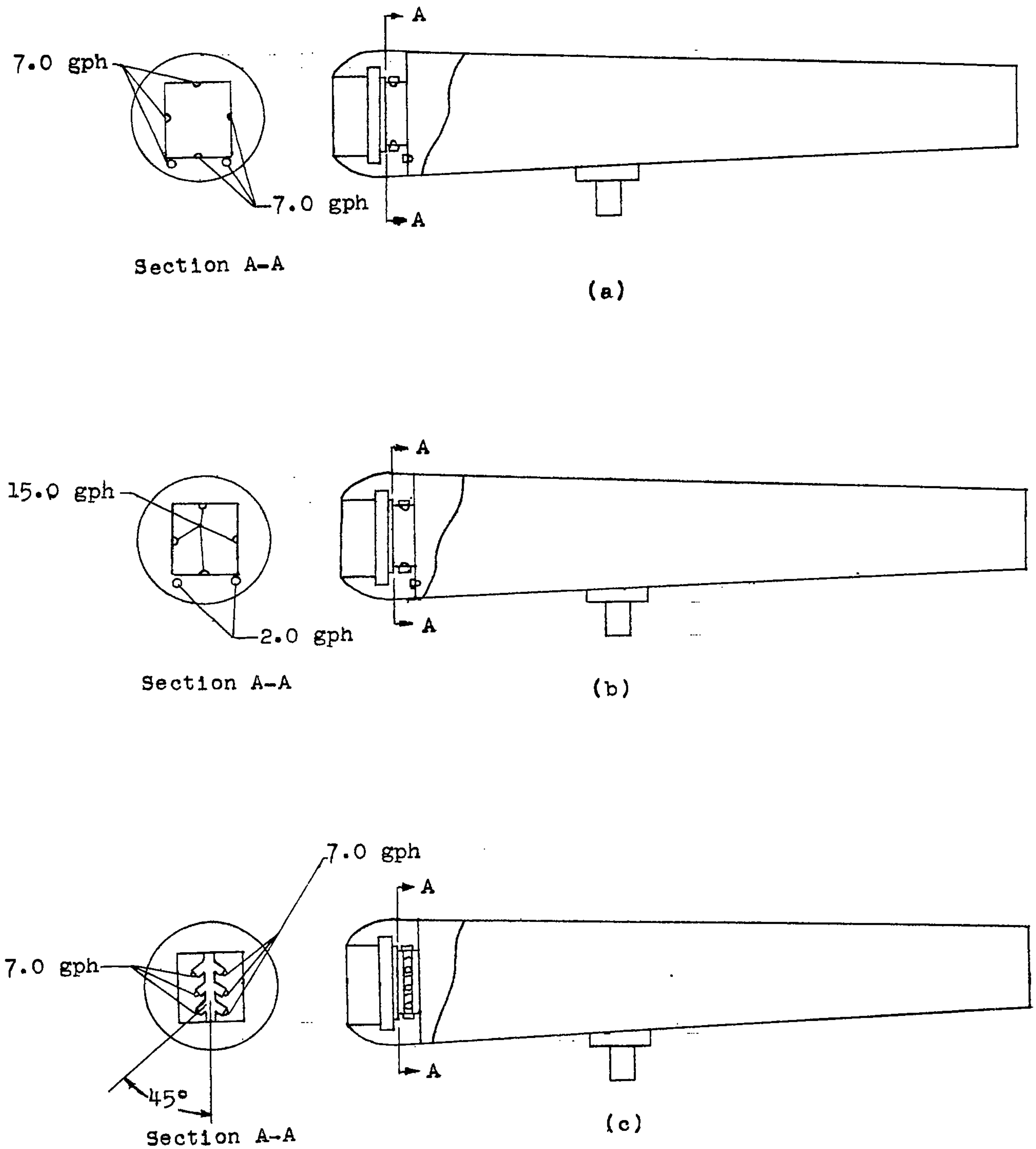
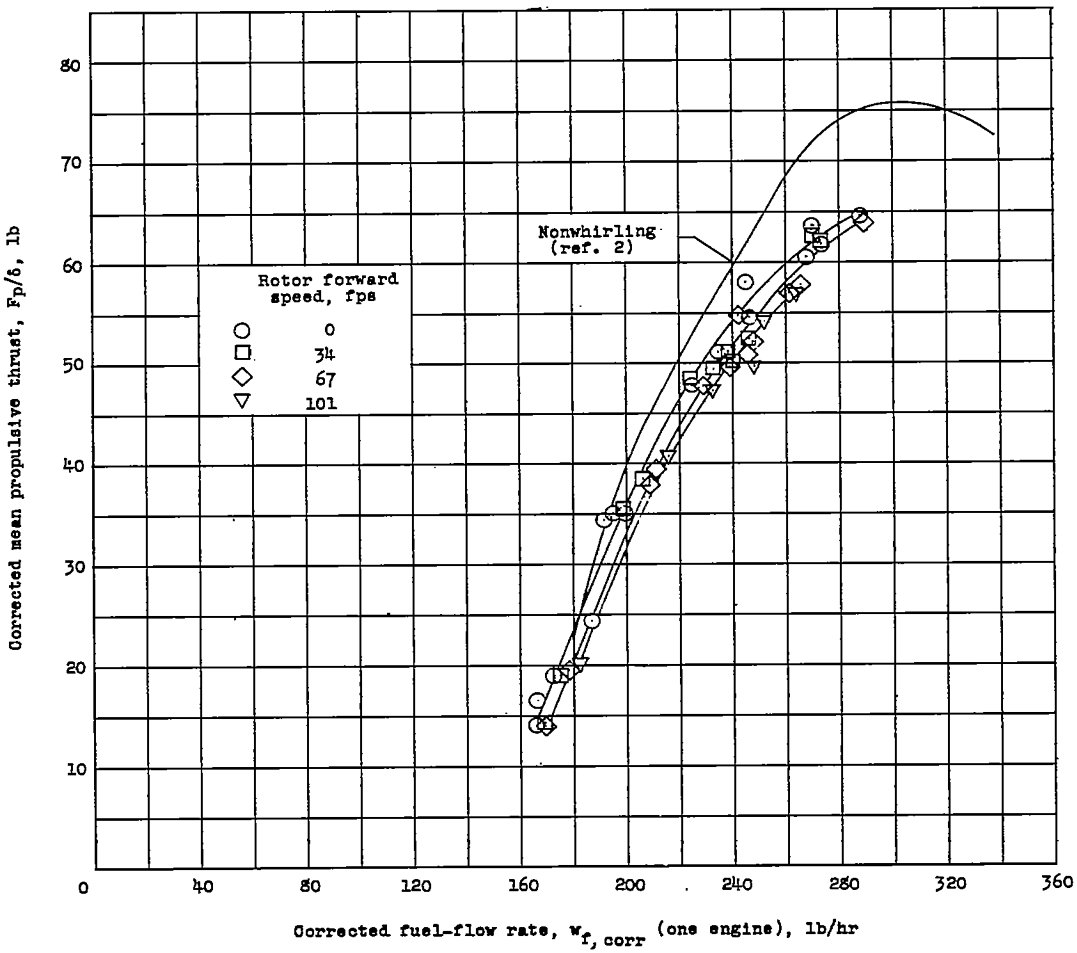
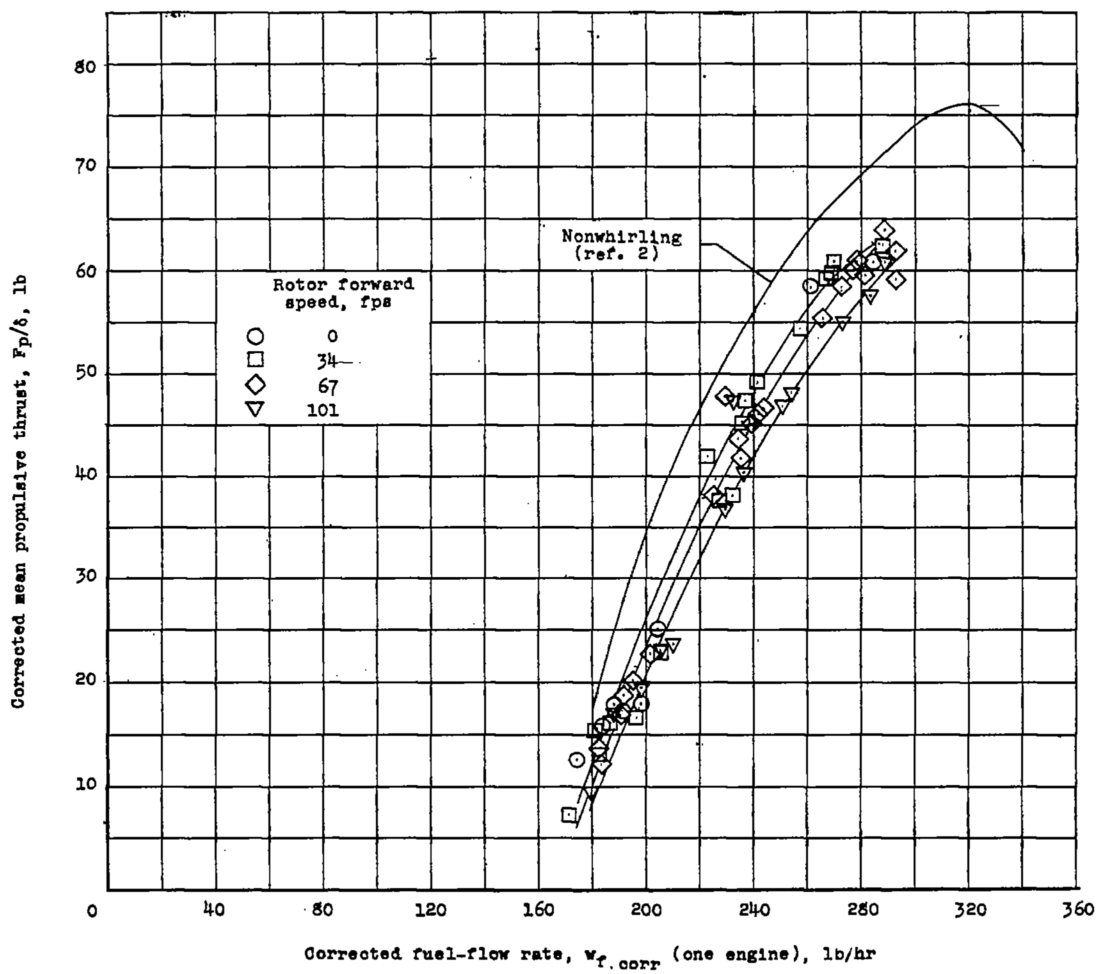


Figure 4.- Pulse-jet-engine nozzle configurations.



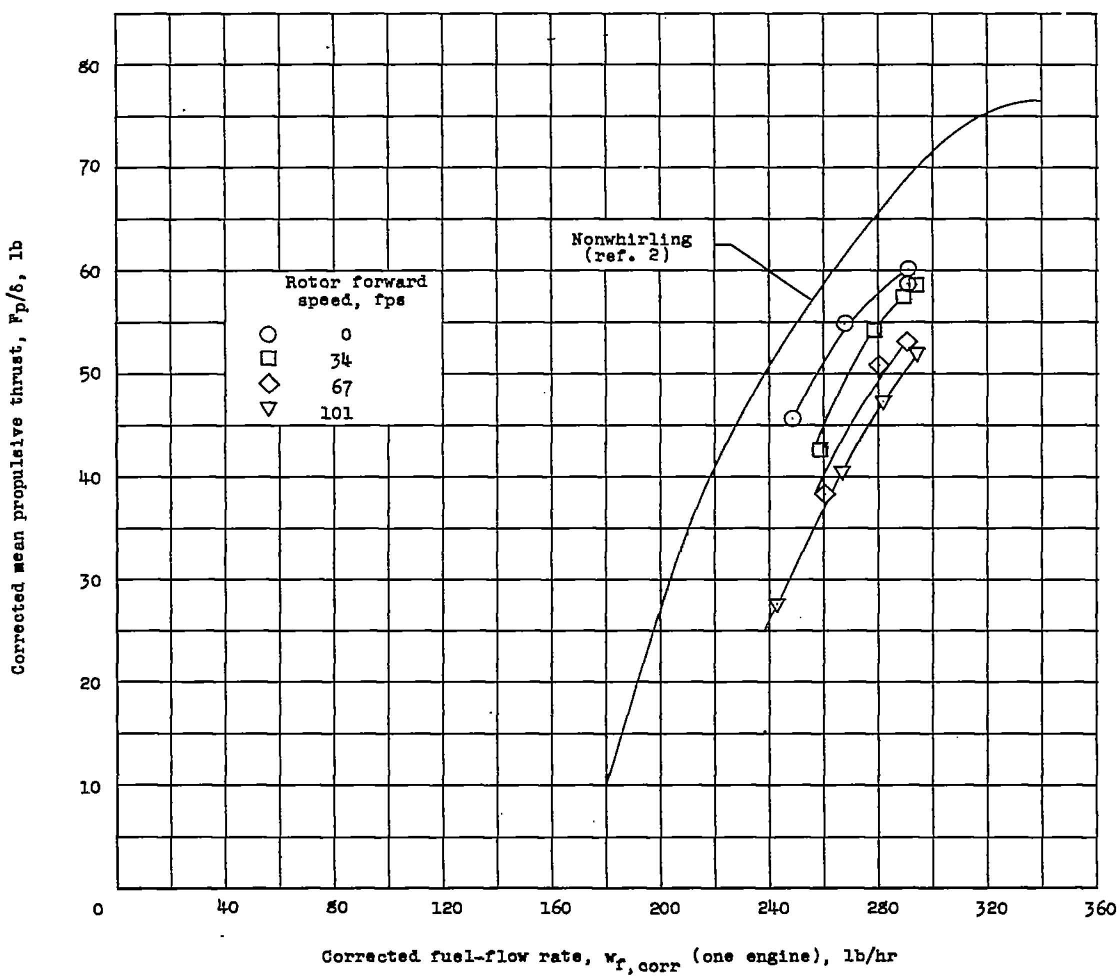
(a) Engine speed, 0.30M or 335 feet per second; centrifugal acceleration, 178g.

Figure 5.- Effect of rotor forward speed on corrected pulse-jet propulsive thrust as a function of corrected fuel consumption for one engine.



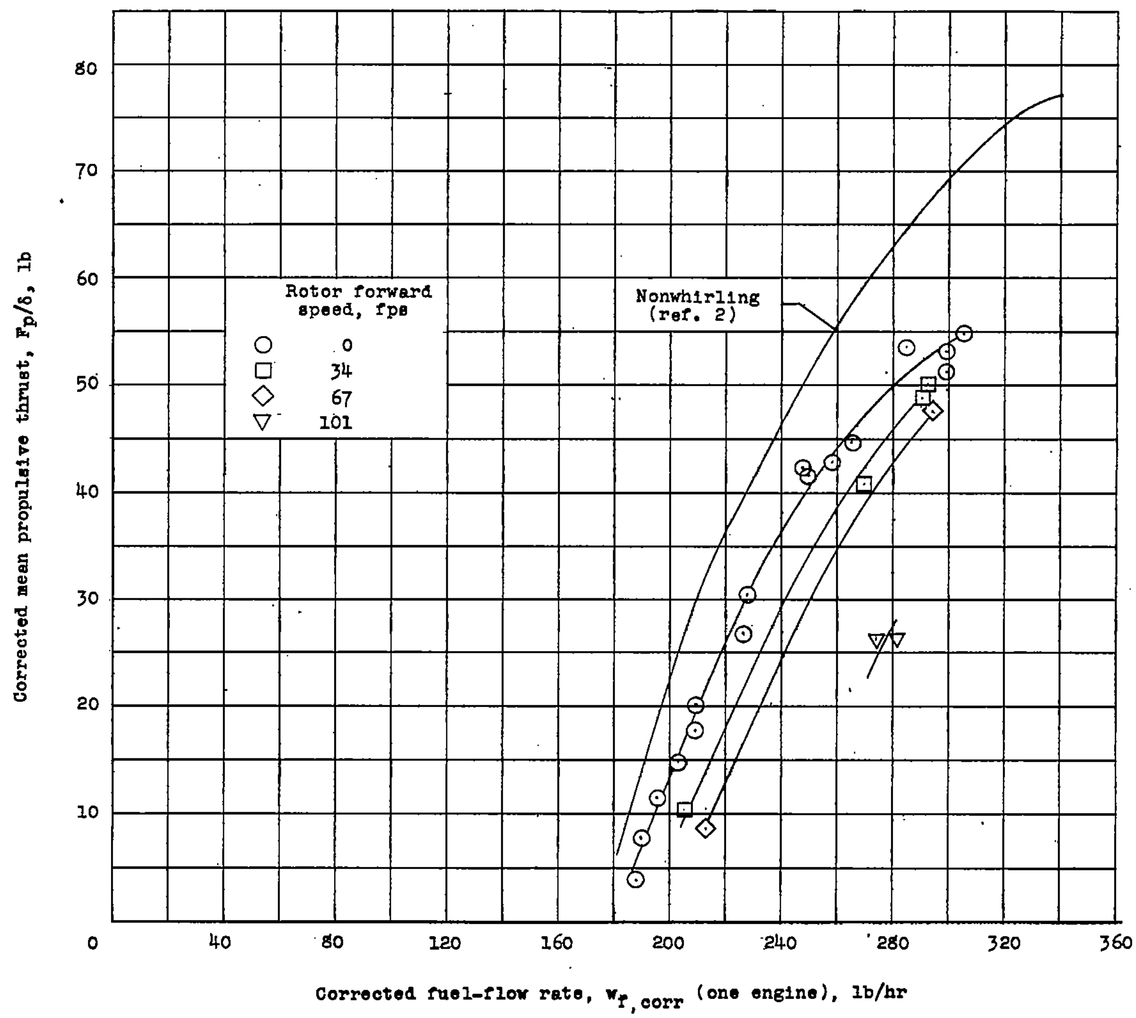
(b) Engine speed, 0.33M or 369 feet per second; centrifugal acceleration, 216g.

Figure 5.- Continued.



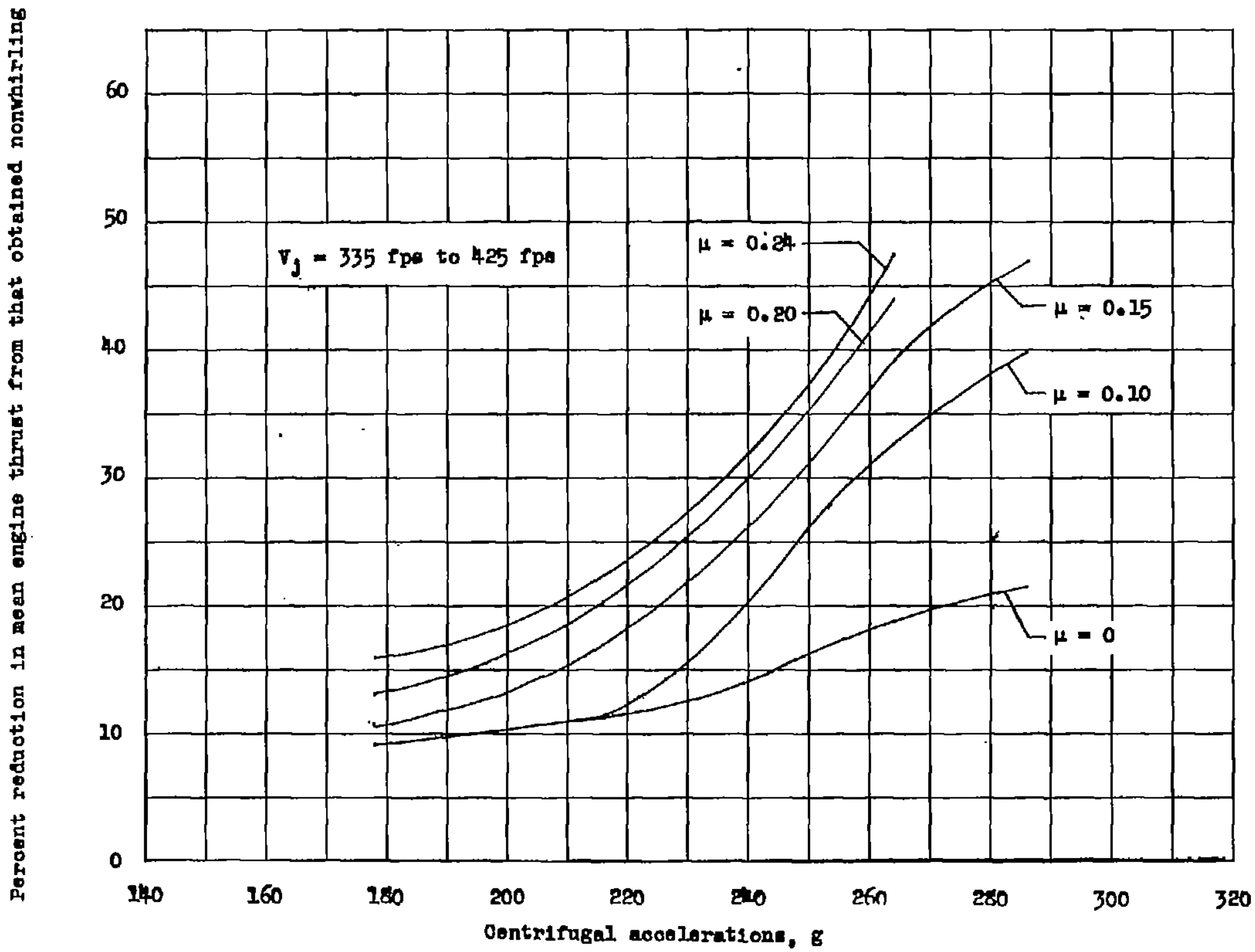
(c) Engine speed, 0.36M or 402 feet per second; centrifugal acceleration, 264g.

Figure 5.- Continued.



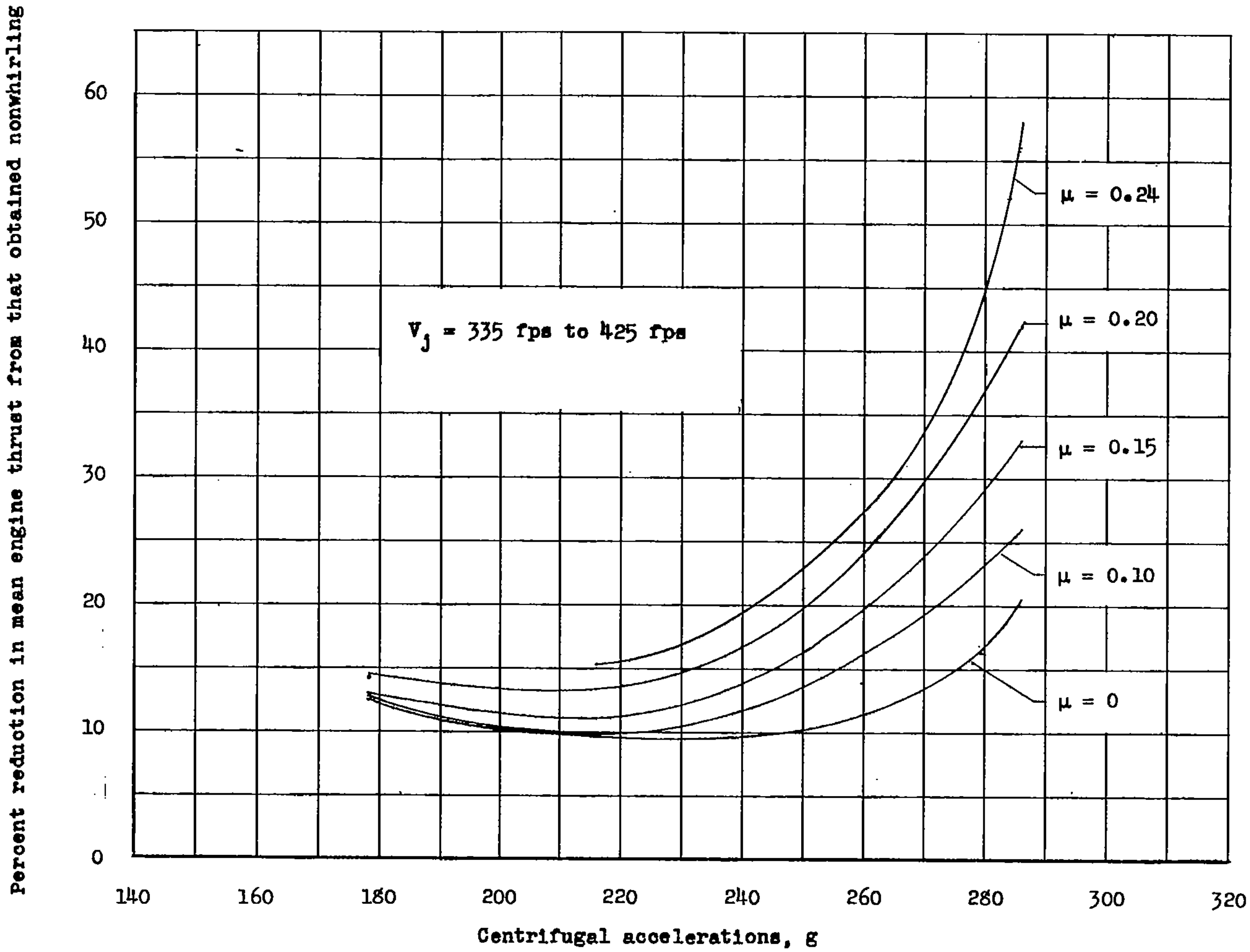
(d) Engine speed, 0.38M or 425 feet per second; centrifugal acceleration, 286g.

Figure 5.- Concluded.



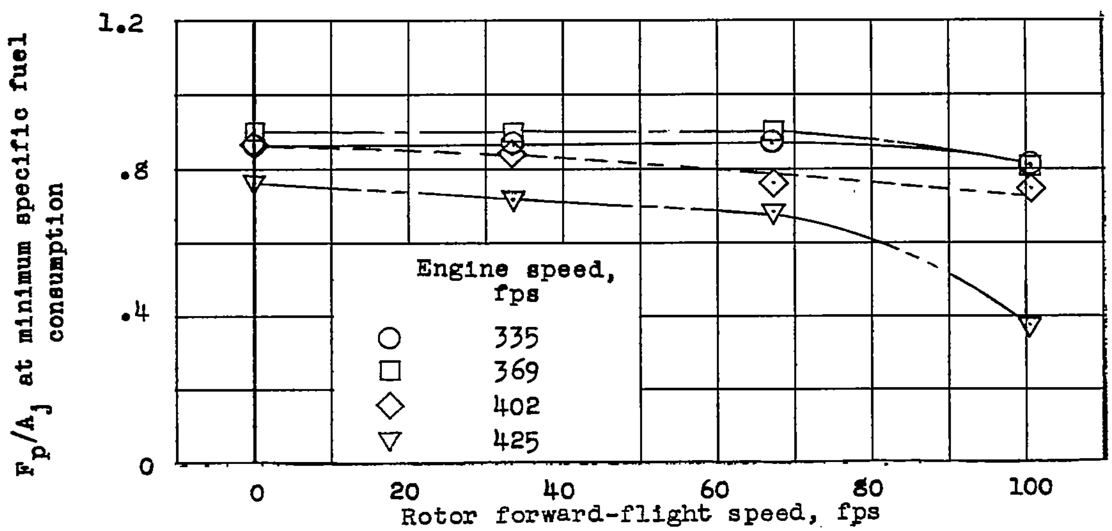
(a) $w_{f,corr}$ = 240 lb/hr.

Figure 6.- The effect of engine-centrifugal-acceleration field on mean engine thrust at various tip-speed ratios.

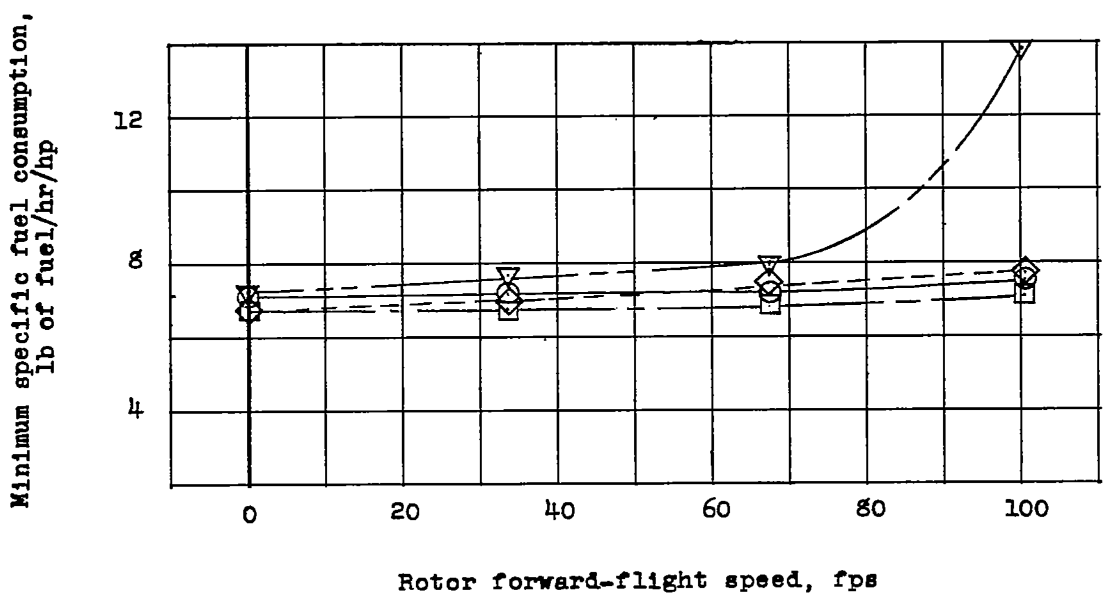


(b) $w_{f,corr}$ = 280 lb/hr.

Figure 6.- Concluded.



(a) Propulsive thrust per square inch of frontal area at minimum specific fuel consumption as a function of rotor forward-flight speed.



(b) Minimum specific fuel consumption whirling as a function of rotor forward-flight speed.

Figure 7.- Effect of rotor forward-flight speed for various engine rotational velocities.

NACA - Langley Field, Va.